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AUTOMATED CROWN REPLICATION USING SOLID PHOTOGRAPHY (SM). (U)

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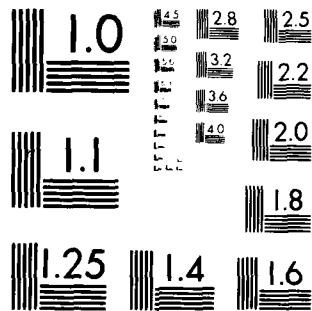
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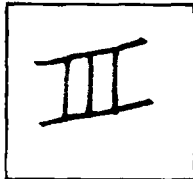


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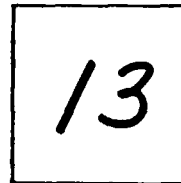
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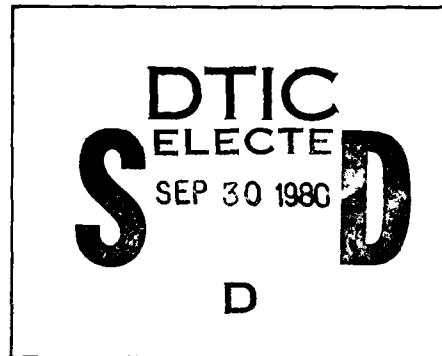
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AUTOMATED CROWN REPLICATION
USING SOLID PHOTOGRAPHYSM
(FINAL REPORT)

R. Schmidt

February 1980

Supported by

U.S. ARMY MEDICAL RESEARCH AND DEVELOPMENT COMMAND

Fort Detrick, Frederick, Maryland 21701

Contract No. DAMD 17-78-C-8055

Solid Photography Inc.
536 Broadhollow Road
Melville, N.Y. 11747

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A research project applying Solid Photography, an optical, three-dimensional technology, to automatic replication of dental crowns out of inexpensive, non-strategic material. This project investigated methods of obtaining complete surface measurement data, preparing this data for compatibility with machining requirements and replicating a dental crown. Measurements were made to an accuracy on the order of ± 0.002 inches on the exterior surfaces of a dental crown pattern and on the die upon which the crown pattern was formed. (continued)		

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20. ABSTRACT (continued)

The data from the die exterior was used to form the crown interior. This project advanced the state of the art from feasibility to the initial stages of machining a closely fitting crown using a computer-controlled end mill following the measurement data obtained by Solid Photography.

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AUTOMATED CROWN REPLICATION
USING SOLID PHOTOGRAPHYSM

SUMMARY

The purpose of this R & D contract was to advance the state of the art relating to automated tooth crown manufacturing. Feasibility of applying the new optical, three-dimensional measuring technology developed by Solid Photography, Inc. was demonstrated on an earlier contract. The current contract was addressed to obtaining a complete, accurate data base that could be used to automatically replicate a tooth crown. The object of automatically milling crowns instead of casting crowns, as is conventionally done, is to obviate the need for using costly strategic casting materials as well as to reduce the labor cost and time involved in producing crowns. Further, it was envisioned that other benefits would accrue by virtue of the fact that the Solid Photography, Inc.'s (SPI) technology inherently produces a three-dimensional digital data base that can be transmitted over conventional communications circuits and used by the many digital resources presently available.

A tooth post fitted with a crown was supplied to SPI to measure and produce a digital data base describing the inner and outer surfaces to an accuracy on the order of $\pm .002$ inch. Special measurement and replication holding fixtures were designed and fabricated to enable precision measurement and replication of the crown's occlusal surface, the four exterior sides of the crown and the five corresponding post surfaces that describe the desired crown interior. The general angular orientation of measurement was optimized to provide maximum coverage of the surfaces with four separate measurements on the crown and four on the post. Replication was done at the same angles to simplify processing and minimize replication time without sacrificing faithfulness of replication. The precision of the instruments simplified processing as well as ensured repeatability after calibration. Ease of use was considered for the eventual production usage.

Calibration software was improved considerably to automate most of the initial calibration. The residual errors were on the order of $\pm .0015''$. More work in this area is needed to reach the goal of an accurate automatically replicated crown. A promising closed-loop, or self-compensating, scheme was investigated that will greatly reduce the effort necessary to provide complete system calibration.

An acceptable tooth surface coating material was identified that meets the hygienic and optical requirements for direct measurement of teeth in a patient's mouth. This material was used on this contract to remove the specular response of the crown and provide opacity for the translucent post.

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Improved computer processing procedures have been developed for an automated crown replication system. However, they still involve much manual intervention and further automation of these procedures are recommended. Some processing procedures have to be improved where significant loss of processed data was encountered. The data loss was caused by the use of relatively unsophisticated software developed for this project. This points out the need for the development of more sophisticated processing software to achieve the objective of the program.

A crown was replicated in acrylic plastic that approached program goals for the exterior replication. The crown interior, however, contained a significant offset error, the source of which could not be identified within the contract period and funding.

The many improvements in the technology relating to automating tooth crown manufacturing has brought that goal closer to hand as a result of the effort on this program. Principal additional effort should be applied toward further processing improvements and reducing calibration efforts.

FOREWORD

Solid Photography provides an economical approach to obtaining the large three-dimensional digital data base necessary to describe a complex surface. This data base is required when a numerically-controlled machine is used to replicate the surface out of a block of material. The desire to eliminate dependence on limited supplies of castable strategic materials and the ever-present need to reduce the cost and time to produce a crown leads inevitably to the use of direct machining. Feasibility of using the process underlying Solid Photography was reported in October 1977 under Contract DAMD 17-77-C-7041.

The follow-on project performed under Contract No. DAMD 17-78-C-8055, which is the subject of this report, addressed the major problems associated with reducing the concept to practice. A device was designed that provided accurate positioning of crown and die to enable measurement of all surfaces. The data required for replication was extracted from the measurement data base. A holding fixture, identical to the measurement fixture, was fabricated to enable precision machining of all exterior and interior surfaces of the replicated crown.

The work performed on the follow-on project provided answers to many of the questions involved in reaching the stated goal. Although the key objective of producing a closely fitting crown, replicated using a three-dimensional digital data base generated by SPI's process has not yet been realized, the capability of achieving this objective as a result of the work performed under the contract has been brought one more step closer to reality.

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1.0 INTRODUCTION

Crowns are presently cast from expensive, strategic materials. The casting process is labor intensive and automation could potentially lower production costs. Numerically-controlled machines could directly replicate a crown from suitable non-strategic and low-cost materials which possess desirable hardness and non-corrosive properties. The key problem confronting this approach has been the inability to obtain the three-dimensional digital data base describing the crown surface rapidly and economically. The crown surface is not easily described by mathematical functions that computers could convert into machine orders. Since each tooth is different, a customized approach was necessary for acquiring the surface data for each one. A rapid, accurate surface measurement system was required.

The feasibility of using the new technology underlying Solid Photography to measure dies and directly machine replicate crown patterns accurately enough to eliminate the standard casting process for producing crowns was demonstrated under Contract DAMD 17-77-C-7041. The results were reported by SPI in October 1977. No attempt was made to modify the existing experimental SPI equipment during that initial contract. Although the equipment was known to be capable of measuring objects the size of a dental crown with .001-inch resolution, to accomplish the objectives of the initial contract, careful calibration of the equipment was necessary to attain the accuracy required for crown replication. In addition, an accurate holding fixture was required to prevent the introduction of errors while measurements were taken from various angles; surface reflectance of the crown and tooth post had to be modified to enable photographic recording of the surface measurements; software procedures had to be developed to invert the exterior tooth post measurements to form the crown interior due to the limited access of the crown opening; and a physical support had to be added by software to hold the crown while surrounding material was cut away. Finally, a stainless steel crown replica was partially machined using the processed data. That replica demonstrated the feasibility of using SPI's process to ultimately automatically produce a finished accurate crown replica to the desired accuracy.

The current report is the result of the follow-on contract (DAMD 17-78-C-8055) in which each of the areas of difficulty, identified during the feasibility study, were investigated in greater depth. A special holding fixture was designed and built to hold the crown and post at a preferred angle for measurement. Calibration was made more automatic to achieve accuracy without the need for manually derived correction factors. An accurate replication holding fixture was built with an orientation identical to the new measurement holding fixture that enabled machining with five axes of movement. A material suitable for use in a patient's mouth was identified that has the necessary surface reflecting properties for use by SPI's 3-D optical measurement process. The new measurement orientation required software modifications to convert the measurement data into a final, merged machining data base. A crown was then machined in plastic using the data base.

A significant improvement in the method of evaluation of the results was made. Since the measurement and replication holding fixtures were identically made, the replica could be measured by SPI's optical measurement process and provide a point-by-point indication of the accuracy of replication. Although it was not possible to reach all program goals in this segment of the development program, the results indicate there are no major obstacles remaining in attaining the ultimate objectives of the program.

2.0 BACKGROUND

A new technology for rapid generation of digital data bases representative of three-dimensional surface locations was announced by SPI in June 1976. In the process underlying Solid Photography, a person sits in the center of a studio with eight cameras aimed at him from various angles to view all surfaces of his head. Then four projectors illuminate him and the cameras record the light patterns cast by the projectors. After developing the film, the film is read by an automatic film reader which generates digital numbers representative of the patterns on the film. A digital computer then interprets these numbers as surface measurements which a numerically-controlled milling machine is programmed to follow. The result produces amazingly accurate and low-cost portrait sculptures.

A Micro Studio Sensor also developed by SPI, capable of making measurements to a resolution of .001 inch in a scaled down volume, was used for the feasibility study and again for this follow-on program. For this program modifications were made primarily to: (1) improve the system calibration by bringing it closer to methods that would be used in a crown replication system operated by low-skilled workers and (2) position (by the use of a special holding fixture) the surface areas measured so that all surfaces of the crown can be accurately replicated. The latter modification was necessary since SPI's existing experimental Micro Sensor System is limited to measuring an object's surfaces that are not oriented close to the horizontal plane. This meant that only three of the five interior or exterior crown surfaces could be measured and replicated. New holding fixtures provided the means of increasing the system's capability to measure and mill all five interior and five exterior surfaces of the crown.

3.0 DATA ACQUISITION

The three dimensional data for the crown were obtained using Solid Photography Inc.'s experimental Micro Sensor modified for this purpose. The modified Micro Sensor consists of a projector, camera and a measurement holding fixture to hold the post and crown. Figure 1 is a photograph showing the crown mounted on the tooth post ready for measurement. The projected light passes through the lens shown to the right of the crown and forms the square area of intense light seen on the crown surface and surface behind the crown. Part of the camera lens can be seen just above the projector lens mount. Three-dimensional data are acquired through a process of projecting

and photographing a series of light patterns on the object. The camera acquires three-dimensional data only on surfaces within its field of view with the restrictions as noted above. Several cameras and projectors are required to adequately cover a typical three-dimensional object if all surfaces must be measured simultaneously. However, when inanimate objects are copied by the Micro Sensor, measurement of all surfaces may be implemented by re-orienting the object in front of the single camera and projector and taking a measurement at each position. The measurement process can be very rapid so there is a good economic tradeoff in designing a production system using just a single camera-projector pair.

The camera is mounted along an axis 45° above the projector axis. It captures data on the occlusal and top surfaces of the crown as mounted since the holding fixture pitches the crown downward at an angle of 22.5° . If the crown were not pitched downward, just the occlusal surface would be properly illuminated by the projector and little or no data would be acquired on the top side of the crown.



Figure 1
Crown Mounted On Post In Measurement Holding Fixture

The tooth post was permanently mounted in a round blank. Four precision positioning holes were drilled into the rear of the blank at 90° intervals. When the blank is placed into the holding fixture, two positioning pins, diametrically opposed, fit into the positioning holes to enable precision rotation in 90° increments to measure the four (non-occlusal) surfaces of the crown exterior and four partial views of the occlusal surface. This precise

positioning allows later correlation of data taken in different views. Features on the occlusal surface not visible in one view, become visible in another view, thus providing complete coverage. The blank is secured to a rear banking surface to assure precise alignment. Repeated measurements confirmed the stability of this measurement system.

Since the inside contours of the crown match the tooth post contours, three-dimensional measurement data on the post can be used (with suitable software inversions) to generate the inside of the crown; hence four views of the post were also measured.

3.1 Measurement Procedure

The system was calibrated and the calibration verified by measuring a cylinder with the Micro Sensor and confirming the measurements using traditional methods. Corrections were made, leaving a residual error on the order of $\pm .0015''$ over the surfaces measured. Repeatability was on the order of $.0005''$.

Because of the translucent nature of the tooth post (similar to natural teeth) which tends to obscure the measurement data, a suitable coating material was sought to make the post surface opaque with reasonable reflectance and very little thickness. A material, de Mark IN[®], manufactured by Holmes Chemical Company of Hatboro, Pennsylvania for locating pressure and binding areas in fixed appliances, was found acceptable. All latter tests on the program used this material.

The post was mounted in the round blank, coated, and then the blank was placed in the measurement holding fixture. The position of the tooth in the measurement volume is not critical as long as it is contained wholly within the volume (0.5 inch cube). The axis of symmetry of the tooth is aligned roughly to the axis of the round blank which is then pitched downward at 22.5° during measurement to maximize the ability of the measurement and replication system to acquire data on all surfaces and machine an accurate copy.

A sequence of pictures was taken. The blank was rotated 90° clockwise and a second sequence of pictures was taken. Similarly, a third and fourth sequence were taken at 180° and 270° clockwise respectively.

The crown was then placed on the post and the process repeated at the four angles.

The film was then developed and read by SPI's standard film reader which directly transmits the digital data to the computer for processing.

Thus, the two problem areas identified in the feasibility study were resolved. The surface coating material proved photographically acceptable and should be hygienically acceptable if required for use in a patient's mouth. The calibration procedure proved adequate to completely calibrate the measurement equipment although not yet as easily and rapidly as originally planned. More will be said later on the topic of calibration when set up of the replication system is discussed.

4.0 HOLDING FIXTURES

Key to the success of the project is accurate placement of the original specimen measured and the replica during machining throughout the succession of steps involved. Each of eight individually placed measurements and eight individual machine set ups are potential sources of error if not carefully controlled. A single fixture was designed and two were built that provided simple, rapid and accurate mounting for measurement and replication. They were machined at the same time to take advantage of compensating errors. Any set-up errors on one would appear on the other as well and the error introduced in measurement would be removed at replication.

A close up of the replication fixture is seen in Figure 2. The side struts provided additional rigidity to resist replication stresses. The measurement holding fixture seen in Figure 1 did not require the struts. The round blank containing the tooth post is placed into the measurement holding fixture and seated against a flat banking surface at the rear of the opening. A positioning pin on either side of that surface provides the correct angular positioning. The entire structure is rigidly held in place after initial alignment. Four screws inserted thru the banking surface from the rear ensured firm contact with the banking surface. Repeatability of measurements was as good as the .0005 inch resolution of the computer printouts. Changing from one angular position to the next can be done in one or two minutes.

The only difference in using the replication fixture, mounted on a standard numerically controlled end milling machine, is that the surfaces have to be carefully cleaned before replacing the round blank to be sure trapped material is not present to cause a positioning error.



Figure 2
View of Replicated Crown in Holding Fixture with Cutting Tool

Since five axes of motion are possible, all five had to be correctly aligned. Figure 3 illustrates the system axes. First in the Micro Sensor the x-y plane of the measurement fixture was leveled. Correction was then made for any x, y or z offset. Finally, the θ orientation was zeroed. A check on a cylinder mounted in the center of the measurement volume confirmed that the ρ axis was centered. All other angular relationships were fixed by the design and not subject to adjustment.

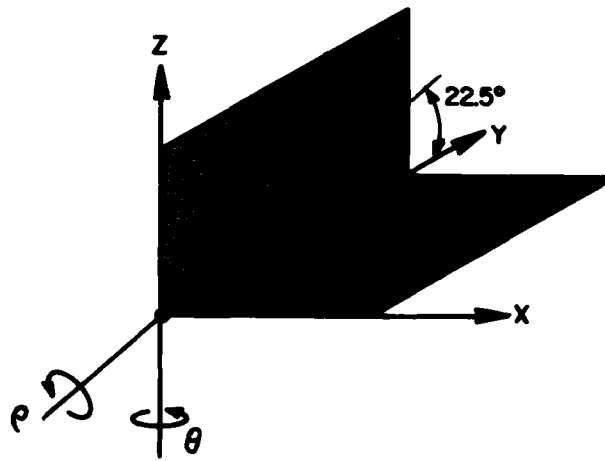


Figure 3
Definition of System Axes

Next the replication fixture was placed on the numerically controlled milling machine. Since leveling of the x-y plane was handled by design, it was just checked and verified. The table was then brought to the known tool center and a trial cut made to verify the location.

Because the two fixtures are identical, it was possible to take the trial cut and measure it with the Micro Sensor. Analysis showed residual fixed offsets of: $-.003''$ for x, $+.003''$ for y and $+.002''$ for z. These corrections were incorporated in the digital data base for all further cuts. The data base for the trial cut was generated mathematically by computer to form a cube to make it easier to determine these offsets.

5.0 PROCESSING

Special consideration had to be given to the 22.5° tilt of the holding fixture. Previously all Solid Photography measurements were made with motions along the principle axes. This precluded combining the data from the four new views into one more complete data base since no software existed to do this. A simplified version of a combining program was written which required considerable manual intervention. It was expected that the crown exterior would have sufficient data to use a single view data base for each of the four exterior cuts. The interior, however, was expected to require data from more than one view if the tool were to be prevented from cutting away material only seen

in a different view. Also when the tooth post data is turned inside out to provide a means of cutting the crown interior, surfaces just behind the shoulder become steep walls preventing entry of the cutting tool (See Figure 4). Thus, this data must be removed before cutting.

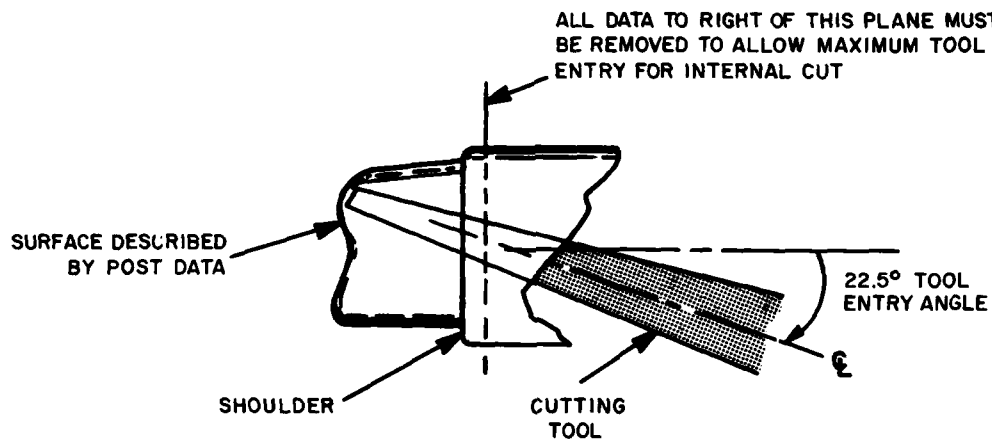


Figure 4
Side View of Post Profile

After cutting the crown exterior, it was evident that gross errors existed. It was hypothesized that this was caused by not having combined data from all four views. The data was reprocessed with programmed limits to prevent the tool from cutting away material from the outside edges when data was lacking. This produced a fairly good replication and essentially confirms the hypothesis. The central areas were not as badly affected by this phenomenon but were sufficiently affected to be detected by the unaided eye. Measuring the replica with the Micro Sensor showed errors less than .002" in some regions but very large errors in other areas. A comparison between the original and replica is shown in Figure 5A and Figure 5B on the following page. Evident in Figure 5B is the lack of detail caused by the use of a .013" diameter tool. A smaller diameter conventional (as opposed to other more exotic cutting techniques e.g. lasers) tool for use in cutting materials of a hardness required for dental crowns is not practical at this time. However, it is our understanding that from a practical point of view it would not be necessary to cut crevices smaller than this size. It is



Figure 5A
Original Crown Exterior

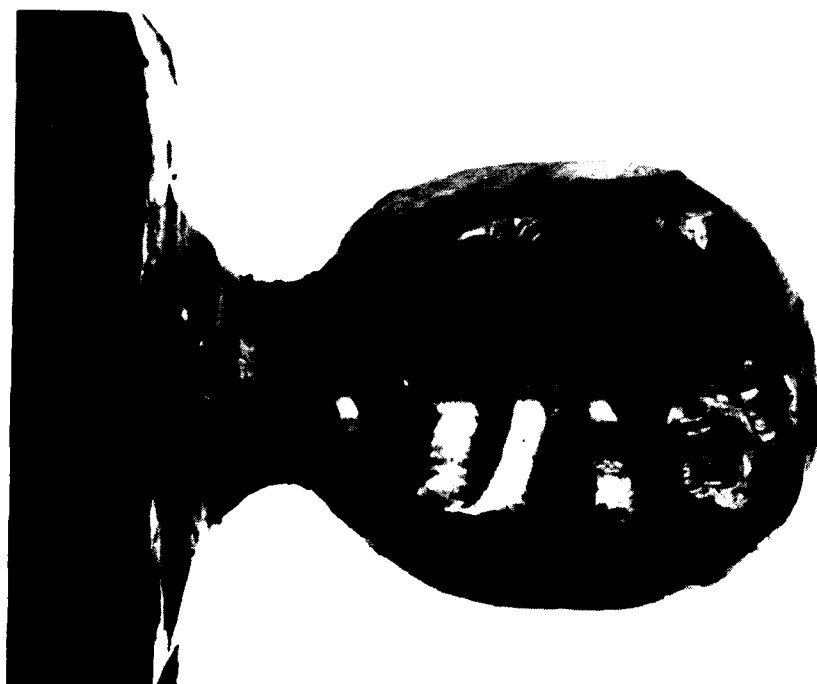


Figure 5B
Crown Replica Exterior

concluded from this experience that data merging from all views is essential. Also seen in Figure 5B at the left of the crown is a mathematically generated support structure to provide physical strength during machining. This was inserted into both the exterior and interior data bases during processing.

The next step, which required much more complicated processing, was to replicate the crown interior. The post exterior measurements were processed in the same manner as the crown exterior up to the point of obtaining a complete data base on each view. Then all the data depth values were subtracted from a constant value greater than the largest depth. This effectively turned the data inside out giving a mirror image. Next the left to right coordinate axis was reversed to complete the reversal of the data base to represent the interior of the desired crown. The edges of the desired surfaces were then manually identified. The mathematical equation for a plane that would separate the desired data from the undesired data was developed. The computer was then instructed to discard all the data on one side of the plane. A mathematically derived support structure surface data base was combined with the data base. At this point, all four views-- 0° , 90° , 180° , 270° --appeared to be at the 0° orientation because no compensation had been inserted to account for the rotation of the round blank. A rotational program was then used to rotate the data bases to their correct relative positions. Rotation of data introduces the complication of hidden lines (i.e. surface data obscured when rotated behind other data) and the unsophisticated software used to resolve the ambiguities lost a considerable amount of good data as well. There appeared to be sufficient residual data to prevent the tool from cutting away material from the crown sides so no improvement was attempted. The rotated 90° , 180° and 270° data were merged with the 0° data and a similar process performed for the 90° , 180° and 270° data bases. Where spot checks were made on the rotated data, it was found that data taken from various views agreed to $\pm .002$ inch in a majority of the checks. The four composite data bases were then processed for tool offsets to obtain the final machining tape to cut the crown interior. Pictorial printouts of the data can be found in Appendix A.

Figure 6A and Figure 6B on the following page compares the original and replica of the crown interior. Large errors are readily apparent but the origin of the errors remain to be determined. Measurement of the replica showed an offset, as compared with the original, of .050 inch which would have to be tracked down before a completed crown interior can be produced.

The lack of adequate interactive computer graphics made processing the data long and tedious. The data is in a form that is not easily comprehended so the computer operator cannot monitor the quality of the data or assess where improvements in the process may be made. For this reason, it is recommended that this deficiency be addressed in the future.

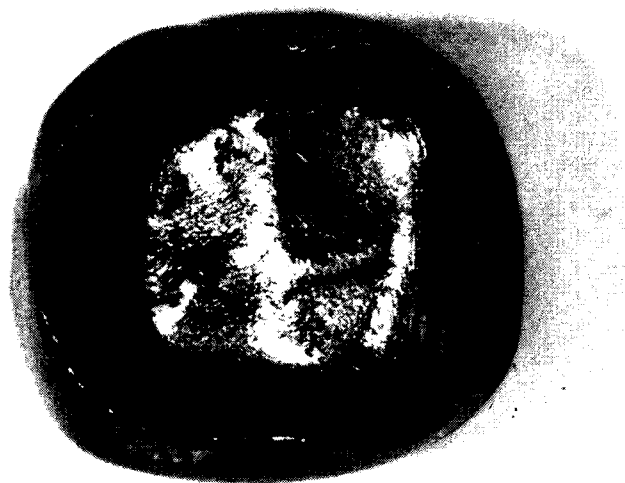


Figure 6A
Original Crown Interior

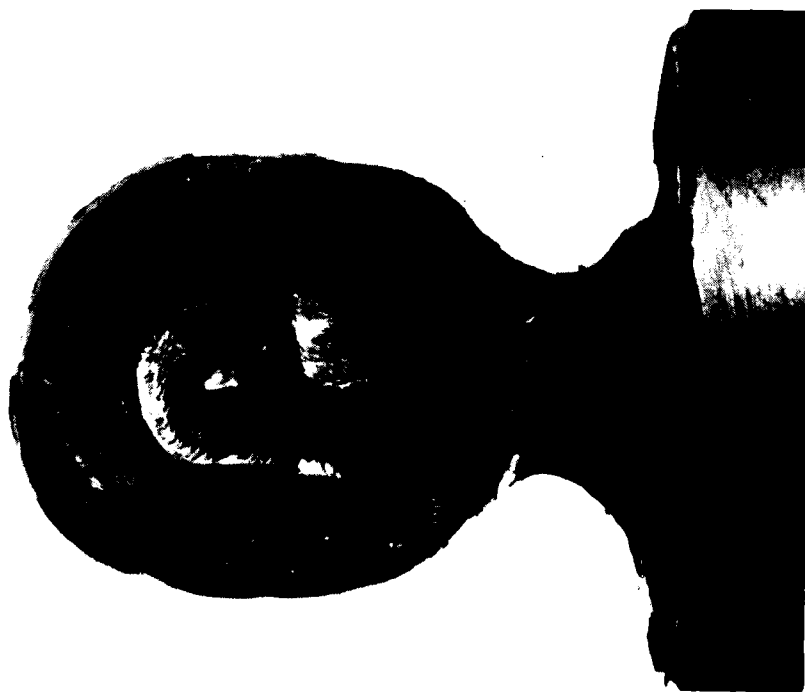


Figure 6B
Crown Replica Interior

6.0 REPLICATION

A standard numerically controlled end mill, modified by Solid Photography, Inc. for the unique requirements of three-dimensional replication, was used to replicate the crown in acrylic plastic. A single flute, 9° taper, cobalt steel cutting tool as seen in Figure 2 was used. It was .018 inches diameter at the tip and was run at 30,000 RPM. The replication holding fixture was designed with access from front and rear. The center of the measurement volume was positioned on the vertical rotational axis so that the inverted post data would be precisely positioned relative to the crown exterior. All machine surfaces were checked for trueness. The replication holding fixture center was then centered as accurately as possible relative to the tool tip. Finally, an inclined cube was cut using a mathematically generated data base and the measured offsets used to make the necessary adjustments to the crown data base.

It was found that to correct for errors introduced by the replication equipment, it was considerably more reliable to cut and measure an object such as the mathematically generated cube, rather than trying to set up the machine by direct measurement. The reason for this is that setting up the system meant tracing all the possible errors in the measurement holding fixture, calibration, and replication fixture--a very large number of independent sources of error. Whereas cutting a known object, measuring it via the Micro Sensor and using the resultant differences as a true measure of total system error brought all errors into consideration at one time in a closed-loop method. This is the recommended procedure for all further work and re-emphasizes the need for simplifying the interpretation of the Micro Sensor data via interactive computer graphics.

Once all errors were known, correction factors were incorporated into the final processing of the data bases for replicating the crown and crown interior. Unfortunately, depletion of time and funding prevented repeating the process for the reversed position of the replication holding fixture, the position used for cutting the crown interior. This would have uncovered the large (.050 inch) offset found in the replication of the crown interior. Any follow-on work should provide for complete closed-loop testing of each of the eight replication stations using the inclined cube data base plus a cross check using a vertical square that can be measured with a micrometer to determine depth and side step offsets. These correction factors combined with a complete merge of four data sets for each of the exterior and interior cuts should reach the program goal of fully automatic replication to better than .002 inch accuracy.

7.0 CONCLUSIONS

Program accomplishments in meeting required objectives:

- Successfully found a tooth surface coating that is thin, opaque, matte finished and safe for use in a patient's mouth. This surface coating is needed to allow optical measurement of translucent or shiny tooth surfaces.

- Successfully developed a method of measuring all crown and post surfaces. This involved modification of the Micro Sensor to eliminate error contributing optical distortions and development of a universal measurement fixture.
- Successfully developed semi-automatic software processing techniques to eliminate unwanted data. An example of such data is the post surface data that would not be in contact with the finished crown.
- Successfully improved the previous calibration procedure to provide a much faster and more accurate calibration of the Micro Sensor. The accuracy improved from .007 inch to .0015 inch residual error.
- Partial success in data reorientation (rotation and translation) was achieved. Although translation was freely accomplished, difficulties were encountered in developing satisfactory data rotation software. The modification of the Micro Sensor measurement geometry to allow the measurement of all surfaces required development of new rotational software. Since this effort was significantly greater than anticipated and due to the limitations of time and funding, the incompleted software which was developed resulted in the loss of some data as the data was rotated. More work is needed to resolve the ambiguities caused by data points rotating behind or in front of other data points which is the cause of the lost data. Further work is also needed to reduce manual intervention in this area.
- Successfully modified SPI's computer controlled replication machine to enable the cutting tool to reach all interior and exterior surfaces of the crown including the difficult interior surfaces. This was accomplished by the development of a universal replication fixture that provided an additional machining axis to the existing four axis milling machine.
- A closed loop correction system was developed under this program that provides an accurate means of calibrating out residual system errors. Philosophically this procedure is analogous to the experienced machinist who cuts a piece slightly oversized, measures the error relative to the desired finished product and then removes the error with a finishing cut. In our case we cut a well-known form (a cube), measure the errors and insert the correction factors for all replications. Unlike the machinist analogy, once the error factors are known, they can be used on all subsequent replications without remeasuring. Since most of the error evaluation was done manually, this is a fruitful area to apply automation.

- Although all the necessary procedures were developed, we were not able to successfully directly replicate a tooth crown in brass within the limitations of time and funding. A preliminary replication in acrylic plastic was made. This replication fell short of meeting the accuracy requirements for the reasons discussed above, but no reason is known that precludes reaching the program goals with continued effort.

APPENDIX A

PICTORIAL PRINTOUTS

DESCRIPTION

Solid Photography measurement data is so voluminous that pictorial representations of the data are the most efficient way to convey the general meaning of the data. This Appendix contains pictorial printouts of the data taken on the sample crown and post used on this program. Each point measured is printed as a dot. The dot's location is a function of the three co-ordinates measured. Distances across the subject are directly represented by distances across the figure. Column sample numbers are printed along the top of the figure. The sample spacings were .002/3 inch apart and printed .005 inch apart giving a magnification of 7.5x. Row samples, referred to as planes in Figure A-1, were spaced .002 inch apart. Depth measurements were quantized into .0005 inch increments. Placement of the printed dot in the vertical direction of each figure were made proportional to the sum of depth and row values.

Figure A-1 shows a view of the crown occlusal surface. The crown was mounted with its axis of symmetry depressed 22.5 degrees below horizontal. The measurement system axis of symmetry was 22.5 degrees above horizontal. The resulting data therefore represents the top part of the crown in the given orientation and the occlusal surface as seen 45 degrees above its axis of symmetry. The pictorial also represents a view above the crown axis of symmetry such that the data lost by shadowing is seen as a white band through the data. The mounting surface can be seen as a flat surface behind the crown. It should be noted that data quality was excellent; the random perturbations of the dots along any one plane can be seen to be on the order of ± 1 to 2 dots or $\pm .0005$ to $\pm .001$ inches.

Figure A-2 is a pictorial of the crown after it has been rotated 90° clockwise about its axis of symmetry. Several shadow areas appear but much of the shadowed areas of the original 0° orientation are now visible. Likewise Figures A-3 and A-4 show the 180° and 270° orientations.

Figures A-5, 7, 9 and 11 show pictorials of the exterior surfaces of the post after removing the crown. The orientations are identical to those for crown measurements. Shown next to these pictorials are Figures A-6, 8, 10 and 12 showing the desired crown interior obtained by merging all the data of Figures A-5, 7, 9 and 11 into a single data base at the 0°, 90°, 180°, and 270° orientations. The mathematically synthesized support structure can be seen at the left in Figure A-6, at the bottom in Figure A-8, at the right in Figure A-10 and at the top in Figure A-12. The mathematical processing only retains the crown lip at the lower part of each pictorial which is sufficient to prevent inadvertent material removal as the tool carves the upper portion of the crown interior. The unneeded data of the lower interior side wall is lost and shows up as a white area on each pictorial. Again the excellent data quality should be noted, completely describing the crown interior and lip with the same $\pm .0005$ to $\pm .001$ inch variations.

DATE = 2 5 80 TIME = 10 34 55
 QUADRANT = 1
 32 96 160 224 288 352 416 480 544 608 672 736 800 864 928 992

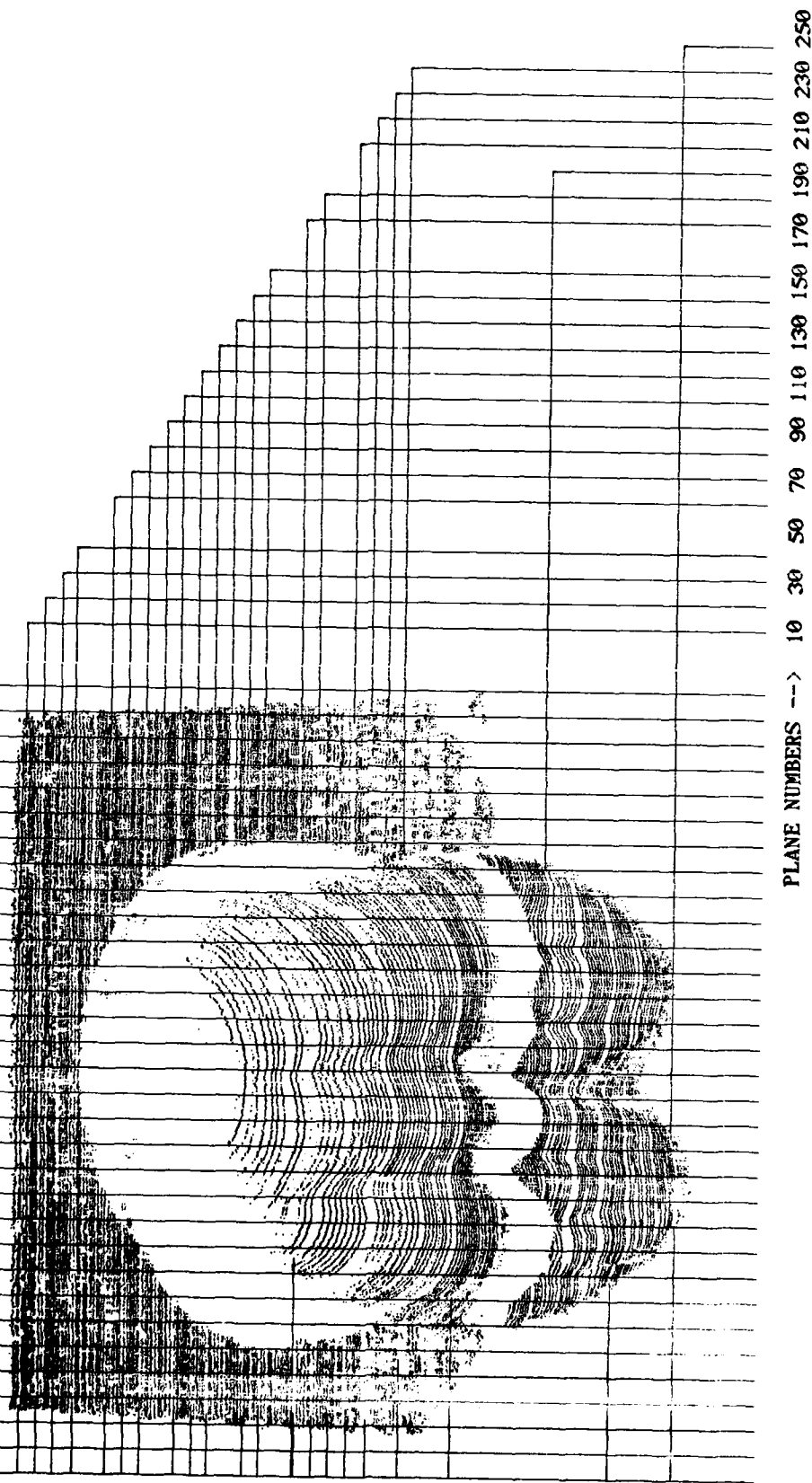


Figure A1 - Crown Exterior 0° Orientation

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TIME = 10 36 51

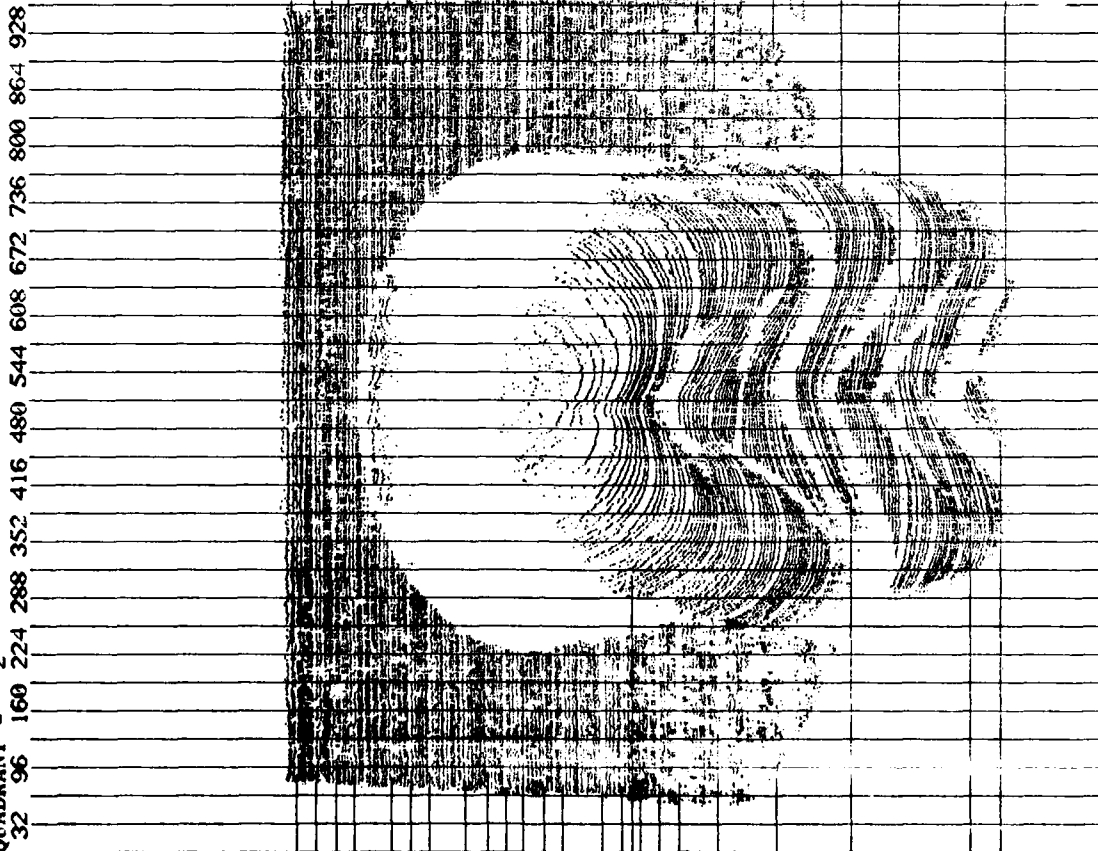


Figure A2 - Crown Exterior 90° Orientation

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TIME = 10 42 5

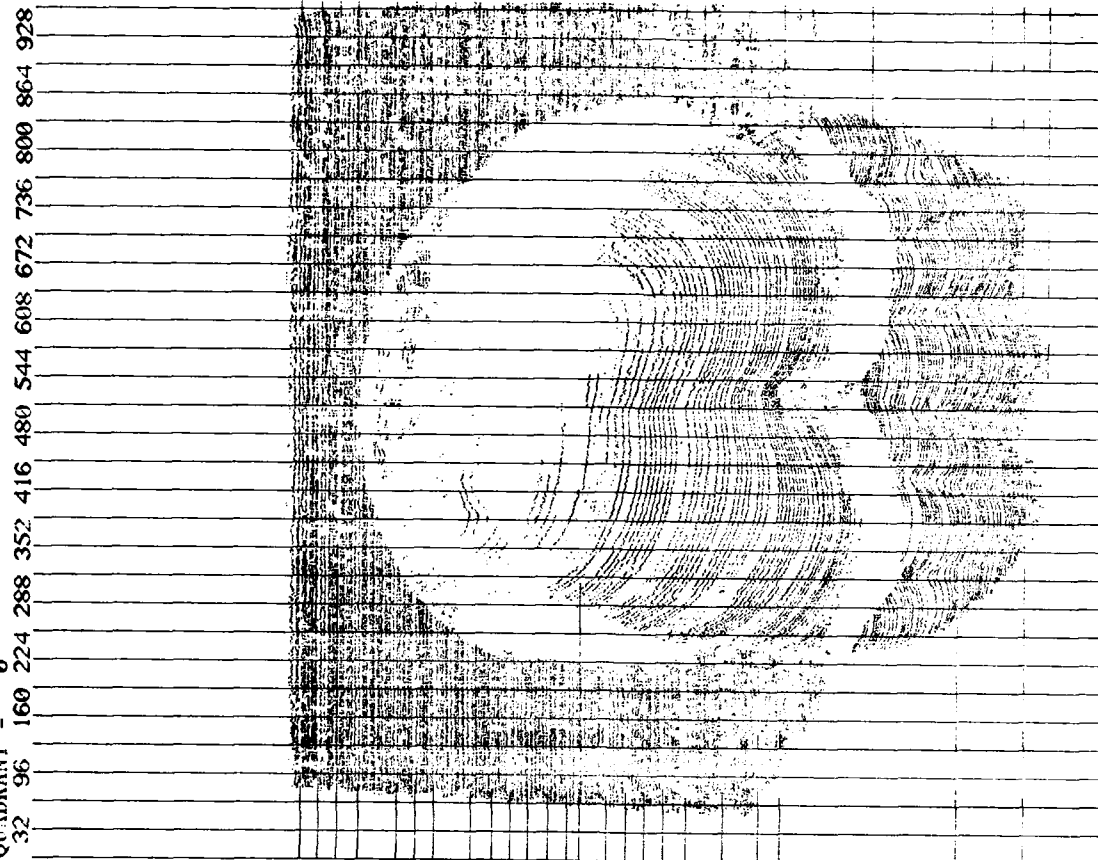


Figure A3 - Crown Exterior 180° Orientation

DATE = 2 5 80 TIME = 10 44 2
 QUADRANT = 1
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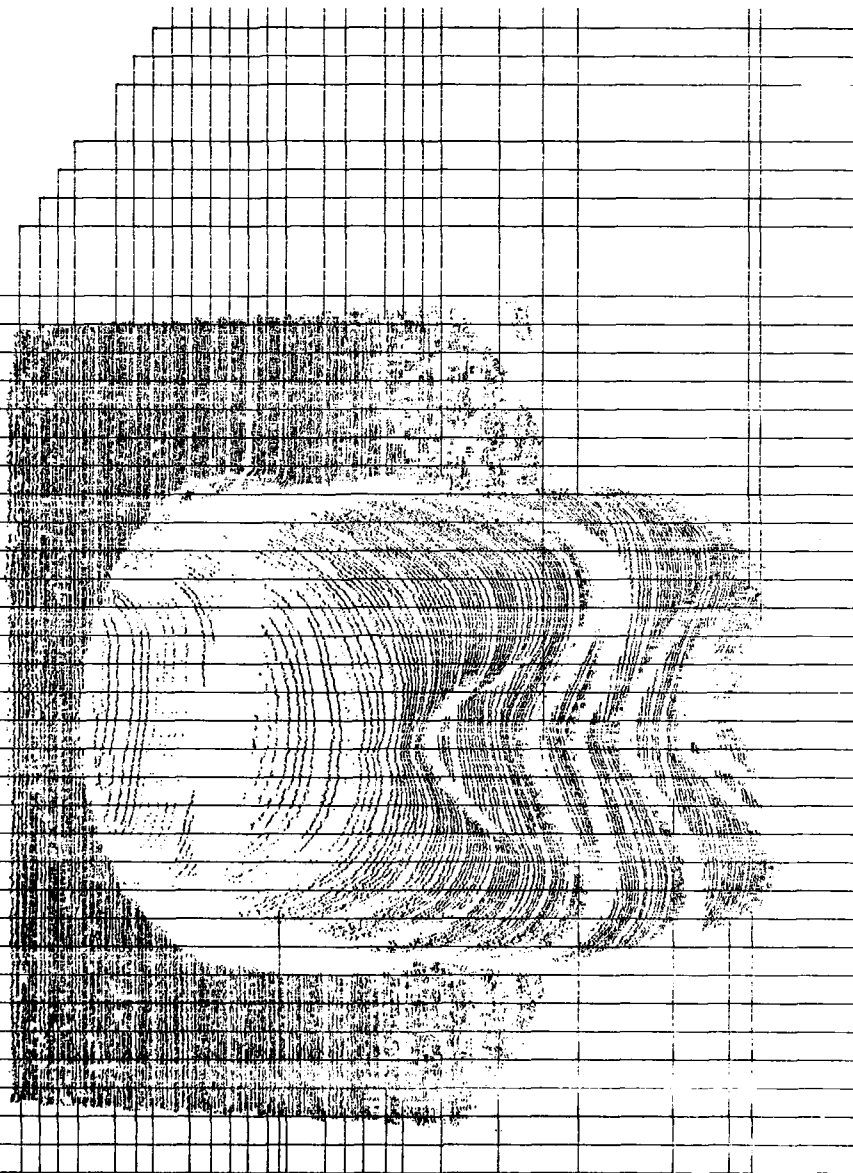


Figure A4 - Crown Exterior 270° Orientation

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DATE = 2 5 80
 QUADRANT = 0
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TIME = 10 20 16

TIME = 10 9 0

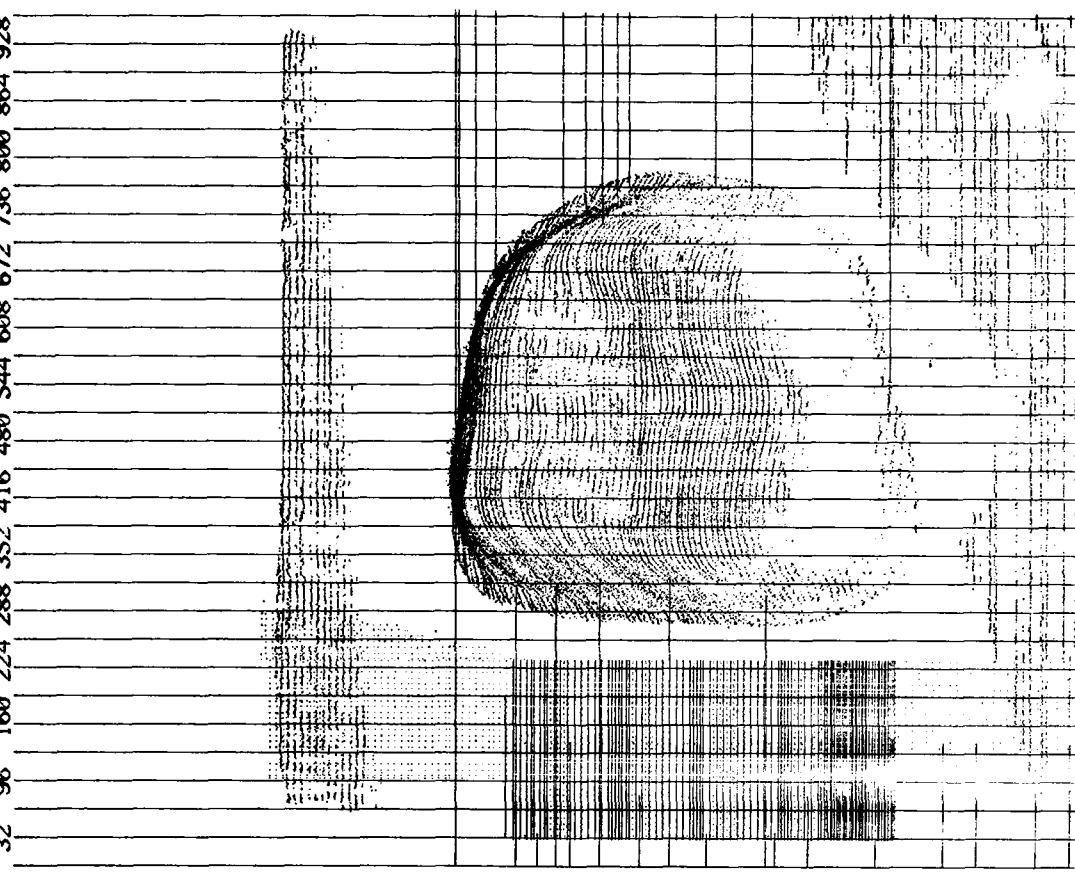
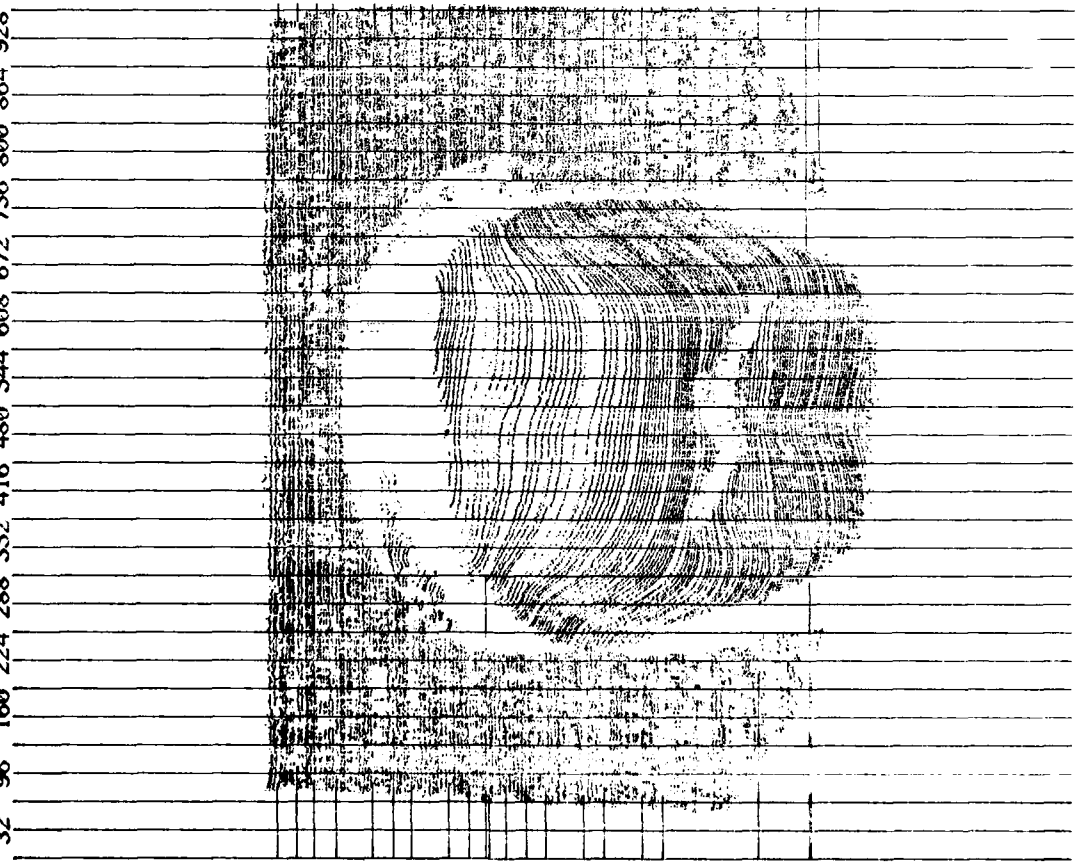
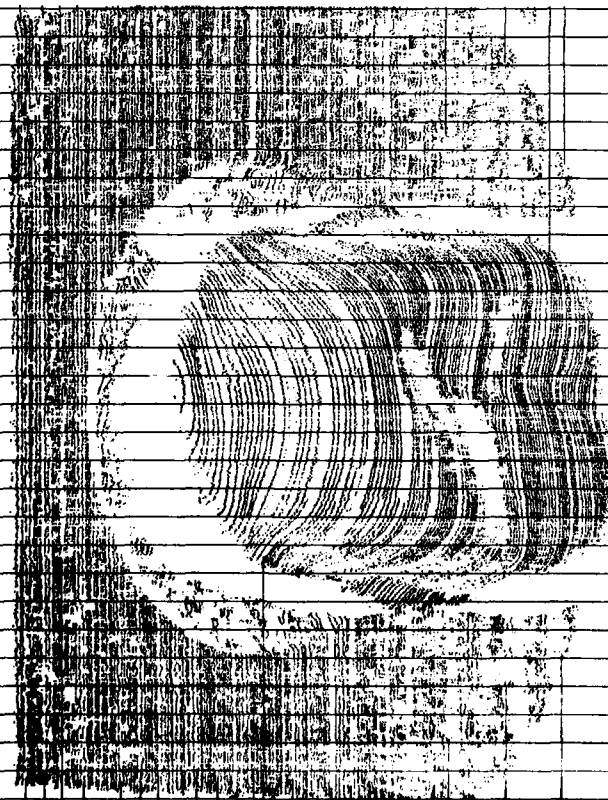


Figure A5 - Post Exterior 0° Orientation

Figure A6 - Post Reversed 0° Orientation

DATE = 2 5 80 TIME = 10 23 29
 QUADRANT = 1

32 96 160 224 288 352 416 480 544 608 672 736 800 864 928



DATE = 2 5 80 TIME = 10 12 9
 QUADRANT = 1

32 96 160 224 288 352 416 480 544 608 672 736 800 864 928

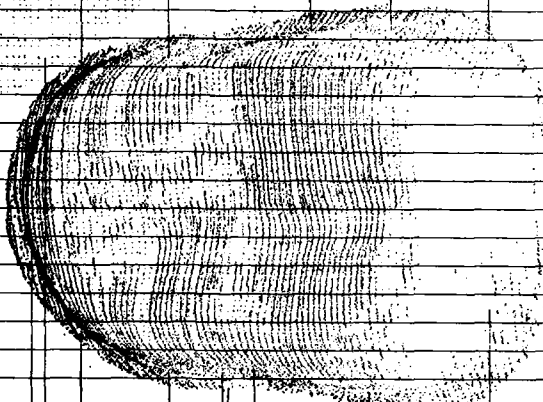


Figure A7 - Post Exterior 90° Orientation

Figure A8 - Post Reversed 90° Orientation

DATE = 2 5 80
QUADRANT = 2
32 96

TIME = 10 25 6

DATE = 2 5 80
QUADRANT = 2
32 96

TIME = 10 13 43

160 224 288 352 416 480 544 608 672 736 800 864 928

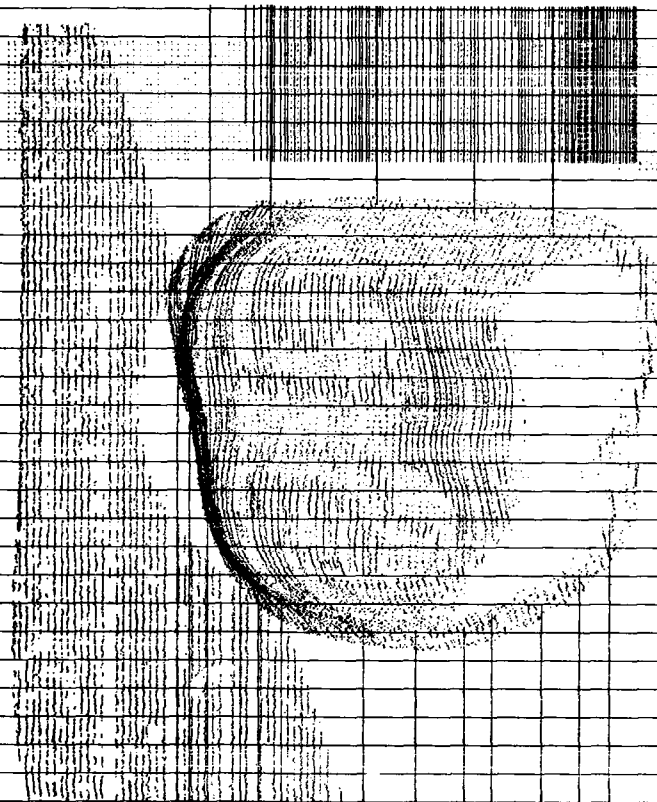
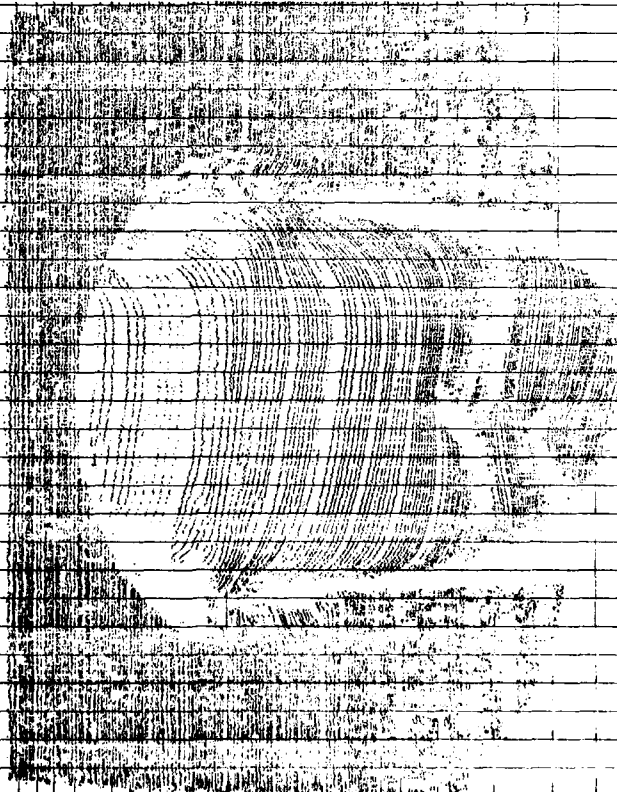


Figure A9 - Post Exterior 180° Orientation

Figure A10 - Post Reversed 180° Orientation

DATE = 2 5 80
 QUADRANT = 0
 TIME = 10 33 6

32 96 160 224 288 352 416 480 544 608 672 736 800 864 928



DATE = 2 5 80
 QUADRANT = 3
 TIME = 10 10 34

32 96 160 224 288 352 416 480 544 608 672 736 800 864 928

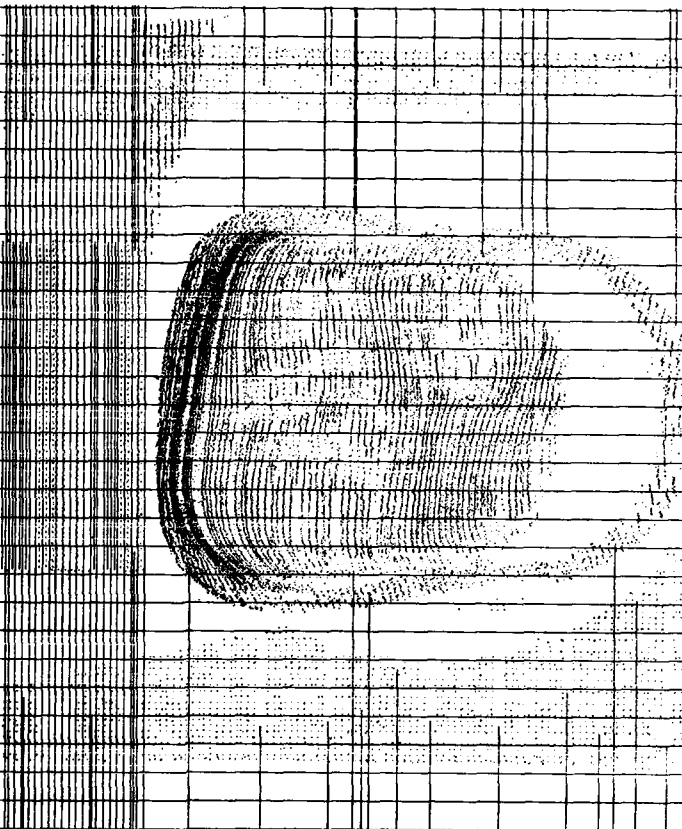


Figure A11 - Post Exterior 270° Orientation

Figure A12 - Post Reversed 270° Orientation

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